Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews
13 (2009) 40–66
RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS
www.elsevier.com/locate/rser

Development and validation of a multicriteria indicator for the assessment of objective aesthetic impact of wind farms

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Received 22 May 2007; accepted 31 May 2007

Abstract

Wind energy represents one of the most important renewable resources. However, despite the fact that wind farms are represented as environmentally friendly projects, they frequently encounter public resistance. One of the main criticisms of wind farm construction projects is directed at their poor aesthetic integration into the landscape. This work develops an indicator to assess the magnitude of the objective aesthetic impact on the landscape caused by the installation of the wind farm. The indicator combines measures of visibility, colour, fractality and continuity which can be taken from photographs. Value functions are constructed for each variable and incorporated into the indicator. This indicator has been used to calculate the objective aesthetic impact of five wind farms. Comparison of the indicator results with a population survey shows that the indicator correctly represents the order of impact as perceived by the population sample, and is thus an appropriate objective measure of aesthetic impact of wind farms.

Keywords: Indicator; Objective aesthetic impact; Wind farm; Landscape; Visual perception; Social validation

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1364-0321/$ - see front matter
doi:10.1016/j.rser.2007.05.002

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1. Introduction

Economic development has been based on access to readily available sources of energy, which are often damaging to the environment. The last few decades, however, have been characterised by growing concern about the environment. As a result, there is increasing demand for "Renewable Energy" which has a low, or negligible, environmental impact. In its Book on Renewable Energies, the European Union set a target for member states to raise the fraction of electricity consumption derived from renewable sources from 6% in 1995 to 12% by 2010. Wind power is an important contributor to the renewable energy mix. Over the last 10 years, global installed generating capacity has recorded a consistent growth of over 20% per year. Europe has dominated the market and by 2004 it accounted for 72.4% of new wind energy installations [1].

The production of renewable energy from wind can have a positive socioeconomic benefit. For example recent technological advances have brought down the cost of wind energy making it competitive with conventional fuel sources [2]. Furthermore, investigations have shown that investment in this type of renewable energy has the potential to enhance economically depressed rural areas [3]. However, despite the fact that wind farms are often represented as environmentally friendly projects, contributing to economic growth, they frequently encounter public resistance. On closer inspection, wind farms are found to have significant impact on their local environment. One of the main criticisms of wind farm construction projects lies in the poor integration of the turbines into the landscape [4]. Often over 100 m tall and of a highly artificial appearance the generators are criticised for their aesthetics [5]. Experience of wind farm projects [6,7] demonstrates the necessity of analysing and evaluating the aesthetic impact of wind farm installation.

A limited amount of work has been reported on the analysis and evaluation of the aesthetic impact of wind farms on a landscape. Such work includes that conducted by Bishop [8], Álvarez-Farizo and Hanley [9], and more recently studies by Hurtado et al. [10] and Möller [11]. The visual perception of a wind farm is influenced by many factors, of which physical attributes such as visibility and colour may be determined objectively. To date, the majority of the studies conducted on objective visual impact of wind farms have concentrated on individual analyses of each physical attribute without consideration of the collective effect of the components.

One way to evaluate the landscape and its components is by means of quantifiable indicators [12]. Numerical evaluation of an impact is desirable because of the straightforwardness with which it can be used in Environmental Impact Assessment. Quantified indicators are also very useful for comparative purposes. Often however, indicators become too complicated, or too specific to be useful in practice. For example, they may require data that are not readily available, or incorporate subjective attribute judgements that are very difficult to quantify. The aim of this work is to develop a user-friendly indicator to quantify the objective, collective, aesthetic impact the construction of a wind farm has upon the landscape.

1.1. Landscape and aesthetic impact

Landscape is a directly tangible, accessible and very important asset for every human being [13]. It is considered one of the most important natural resources both from naturalistic and socio-economic standpoints [14]. It is this notion of landscape that this work seeks to adopt, namely landscape as the perceptible embodiment of the interrelated physical-natural and socioeconomic system [15]. This definition suggests that we should consider the landscape concept in terms of environmental, economic, and human/societal domains. Visual impact falls within the human/societal domain. In this paper we value landscape in three different ways: from a scientific and cultural point of view a landscape is valued for its ecological diversity, its rarity, and for the landmarks inherited from history and culture; from a utility point of view it is the functionality of the landscape that counts; finally there is the visual appeal, which is a question of aesthetics. This is shown in Fig. 1.

Given that aesthetic impact belongs to the human/societal domain, it comprises both an objective part which includes physical characteristics of the landscape, and a subjective part which involves human perception of the landscape. For example a larger turbine will have a greater impact than a smaller one (objective component). This difference may be

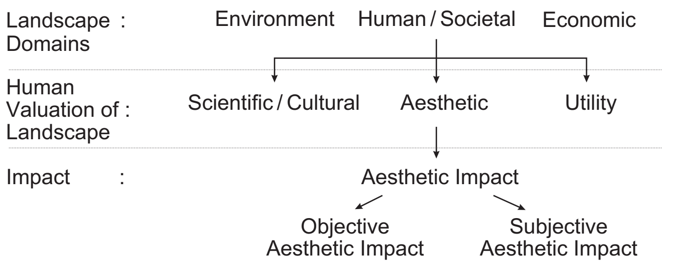

Fig. 1. Landscape and aesthetic impact: the figure shows the three landscape domains. In bold are the issues of interest to this work. Aesthetic valuation of landscape falls within the human/societal domain. Aesthetic valuation is the response to an aesthetic impact, which is made up of objective and subjective parts.

perceived differently by an external observer, compared to the local resident who may find the turbine unacceptable regardless of its size. Considering human perceptions thus introduces a subjective component. The indicator introduced in this paper deals with the objective component.

1.2. Measuring visual impact

One way to quantify visual impact is through the use of indicators. Indicators play an important role in Environmental Impact Assessments, where the impacts are valued quantitatively wherever possible. A literature review of studies on landscape assessment reveals that there is currently no comprehensive system of visual impact indicators. There is clearly a need for field professionals to be able to quantify the visual impact generated by changes in the landscape with an easy-to-use, readily available general formula.

Two conventional methods exist for the development of an indicator of environmental impact, the expert approach and the public preference approach [16–18]. The first method requires the contribution of experts in the field whereas the second relies primarily on the subjective judgement of the participants affected by the project. The expert approach seeks to devise ways of measuring physical attributes of the landscape to reflect visual quality. This process is carried out by skilled and trained experts in the field, in a procedure which generally involves verbal or numerical characterisation of the landscape parameters. The landscapes are usually depicted in photographs, although other means of representation are also possible. Because this type of methodology can be easily applied in a wide range of fields, it is especially useful in problem-related research, particularly for landscape planning and management. This approach has been widely used in the literature (for examples see [17]). In this work, we will apply an expert-based methodology to develop an indicator of objective visual impact of wind farms.

1.2.1. Positive and negative visual impacts

Whether a visual impact is positive or negative is determined through cognition; it is the observer viewing the wind farm and processing the information who decides whether the impact it approved of, or not. Hence, determining the approval of a visual impact would require a subjective investigation of the viewer population by subjective opinions.

The purpose of this investigation however, is to study objective visual impact. Therefore, this work will not seek to establish the approval or disapproval of the impact, rather it will present a method to determine the size of the impact, its magnitude.

1.2.2. Visual impact significance—the objective component of visual perception

The degree to which an object affects its surroundings is named impact significance. Impact significance comprises a set of basic criteria, supplementary criteria and quality criteria [19]. Two basic criteria, the magnitude of the impact and its spatial extension, are of particular interest to this work. It is important to distinguish between these two criteria. Magnitude refers to the difference in visual quality induced by placing the object in the landscape. Conversely, spatial extension means the physical extent of the impact, which will vary depending on the viewshed. The objective of this work is to provide an indicator to quantify the magnitude of a visual impact.

2. Steps to develop an indicator of objective aesthetic impact of wind farms

The need to exploit optimum wind conditions requires wind turbines to be placed on highly visible locations such as summits and flat expanses of land. Producing large amounts of energy also requires the use of many turbines. From a study of the literature, we suggest that the variables affecting visual impact of a wind farm are the visibility of the wind farm, the colour, and the fractality of the turbines. The way in which the turbines have been laid out, i.e. the farm's continuity, too can influence the overall appearance of the farm [20,21]. Each of these variables affects aesthetic impact differently and so construction of an Indicator of objective aesthetic impact of wind farms (hereafter referred to as OAI_{WF}) thus requires the development of an individual indicator for each one of these variables: an indicator for the objective aesthetic impact due to visibility (I_v), an indicator for the objective aesthetic impact due to colour (I_{cl}), an indicator for the objective visual impact due to changes in the fractal dimension (I_f) and an indicator for the objective aesthetic impact due to continuity (I_{ct}).

2.1. Generating the value functions I_v, I_{cl}, I_f and I_{ct}

OAI_{WF} should enable comparison between impacts generated by different types of farms on different types of landscape. Consequently, for every combination of farm type and landscape type, each I_v, I_{cl}, I_f and I_{ct}, will be a function of the contrast between the farm and the surrounding landscape. Thus for example, placing a blue turbine against a grey sky will introduce a contrast in colour, which will generate an impact I_{cl} of value X.

Photographs were taken of different wind farms with varying contrasts in visibility, colour, fractality and continuity, and the ratios were calculated. The calculation procedures for each variable are shown in Section 3. Minimum and maximum ratios were assigned impact values of 0 (no impact) and 1 (total impact), respectively. The photographs and their respective results were presented to a panel of 10 environmental sustainability experts, who were asked to evaluate the visual impact induced by each variable on a scale of 0 to 1. Subsequently, individual value functions were created for each I_v, I_{cl}, I_f and I_{ct}.

2.2. Construction of the indicator

I_v, I_{cl}, I_f and I_{ct} are combined in a final formula to give the OAI_{WF} installed on a landscape. This formula takes the form of a weighted sum, in which the weights have been given by expert judgement and analysed by means of the analytical hierarchy process (AHP).

2.3. Validation of the indicator

To ensure thorough validation of the index proposed, three types of validation are considered for this study: Sui validatio or design validation, Scientatis validatio or output validation and Societatis validatio or end-use validation [22,23].

2.4. Data

2.4.1. Study sites

For the development of the indicator, three sites with different characteristics were chosen as backgrounds for the study, namely a flat-land area, a mountainous area and a rocky area. Wind Farm A is found in the region of Cuenca (Eastern Spanish Inland) and is located along the motorway leading to the Spanish capital city, Madrid. This farm was chosen for the flat land analysis. Wind Farm B is found in the natural protected parks in the mountainous region of Tarifa (Southern Spanish Coast), and Wind Farm C is sited in a town near the city of Valencia (Eastern Coast) on a rocky landscape.

The validation of the indicator required the analysis of two further wind farms, both located in the green landscapes of Cardiff (Wales). Wind Farm D is sited on a forested mountain top, and Wind Farm E is built on a field in the vicinity of two villages.

2.4.2. Photographic representation

This study uses photographic representations of landscapes. The validity of photographs in landscape assessment is well documented throughout the literature and is now widely accepted [24–26].

For each study site, a map of the area was used to identify all the points from which the wind farm could be viewed and which were easily accessible to people, such as motorways, points of scenic value and roadside restaurants. Their position was later confirmed in situ. Locations with the highest number of visitors were chosen for the analysis. Once at the observation points, the views were subdivided into close-up views, middle plane and far planes, depending on the size of the area enveloping the wind farm. A close-up view of a wind farm is one for which the area required to enclose the farm takes up more than 33% of the actual view. Middle planes were characterised by wind farms taking up between 15% and 33% of the actual view and far planes are distinguished by wind farms covering less than 15% of the view. This categorisation is taken from the law of land planning and landscape protection (Valencia, Spain), but is thought to be a reasonable approach in general.

From each location, panoramic photographs are taken of the entire expanse of the wind farm and grouped into the corresponding planes. In cases such as roads, where the pictures can be taken from different positions, the photographs should be made from those points

which offer maximum visibility of the farm at each plane. For the analysis of fractality, the process is repeated at different times.

3. The value functions

3.1. Visibility

The concept of visibility refers to the degree to which it is possible to see within a certain territory, through a certain medium [27]. Introduction of a wind farm into a landscape will decrease the amount of area visible, thereby obstructing the view of the background. Furthermore, a greater number of turbines and a greater size of turbine will result in a stronger visual impact [28]. Referring to the definition of impact magnitude [19], this may be understood as: the larger the total area of the farm, the greater the change of the background view and hence the higher the visual impact. Thus the ratio between the area occupied by the intervention and the total landscape area appears to be positively related to visual impact.

The next step is to describe how changes in this ratio affect visual impact. Ratios were calculated for five different photographs by comparing the sum of the areas occupied by the individual turbines (i.e. the area occupied by the farm (S_{fa}) to the area taken up by the initial background landscape (S_{ba})). The area of a turbine was calculated using Photoshop by combining the area of the mast with the area of the ellipse formed by the rotation of the blades. The expert evaluation showed that I_v can be described as (Fig. 2)

$$I_v = \begin{cases} 0.184x & \text{for } 0 < x \leqslant 0.7, \\ -0.003x^2 + 0.114x + 0.051 & \text{for } 0.7 < x \leqslant 12.3, \\ 1 & \text{for } 12.3 < x \leqslant 20, \end{cases} \tag{1}$$

where I_v is the aesthetic impact due to the visibility of the wind farm, S_{fa} is the area occupied by the turbines in view, S_{ba} is the area of the photograph, and $x = 100 \cdot (S_{fa}/S_{ba})$.

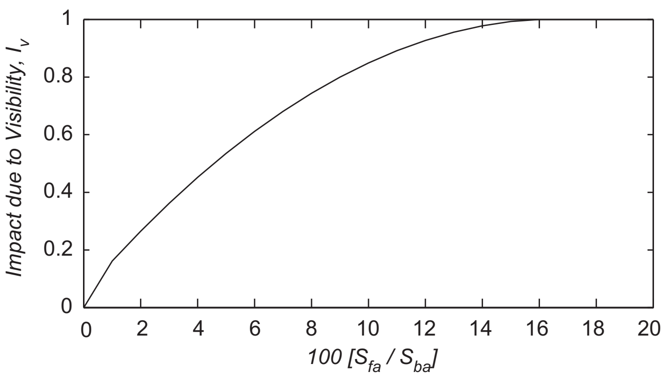

Fig. 2. Value function I_v as given by the experts.

When there are no turbines in the landscape, the impact perceived by the observer is zero. Visual impact increases with the number of turbines and reaches a maximum value of unity when the farm makes up 15% of the view.

3.2. Colour

Colour is defined by three parameters, namely hue, saturation and brightness [27]. Differences in these parameters can generate contrasts in colour and affect aesthetic impact. These differences can be calculated using the CIELAB colour formulae [29] and methods introduced by García et al. [30]. Both techniques produce equally valid results. However, because of the simplicity and applicability of the colour formulae, the authors have decided to apply the CIELAB method to analyse colour contrasts. For each turbine, mean values of the three characterising parameters known as the *L*, *a*, *b*, parameters were obtained using Photoshop. Different turbine colours produced different results of the formulae. Similarly, mean values of the *L*, *a*, *b*, parameters were calculated for the area surrounding the farm. As suggested by Bishop [31], in such cases where the object does not display major colour variation, as is the case of a wind turbine, the background area to be considered in the analysis should be that of a surrounding ellipse, a little bigger than the object itself (Fig. 3).

The CIELAB formulae calculate differences in *L*, *a*, *b* values between two objects and from this, generate CIELAB points. CIELAB points were calculated for nine combinations of turbine colour and background colour, and assessed with respect to aesthetic impact. Fig. 3 presents two examples. The function resulting from expert

Fig. 3. Examples of colour contrasts between a white turbine and (a) a clear background (CIELAB points = 1508.5, and (b) a background in a rainy day (CIELAB points = 454.5).

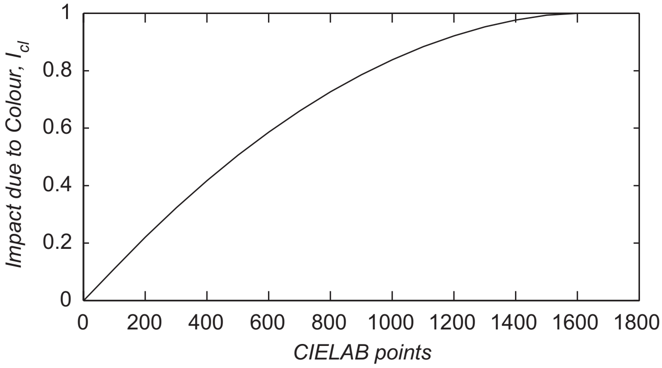

Fig. 4. Value function I_{cl} as given by the experts.

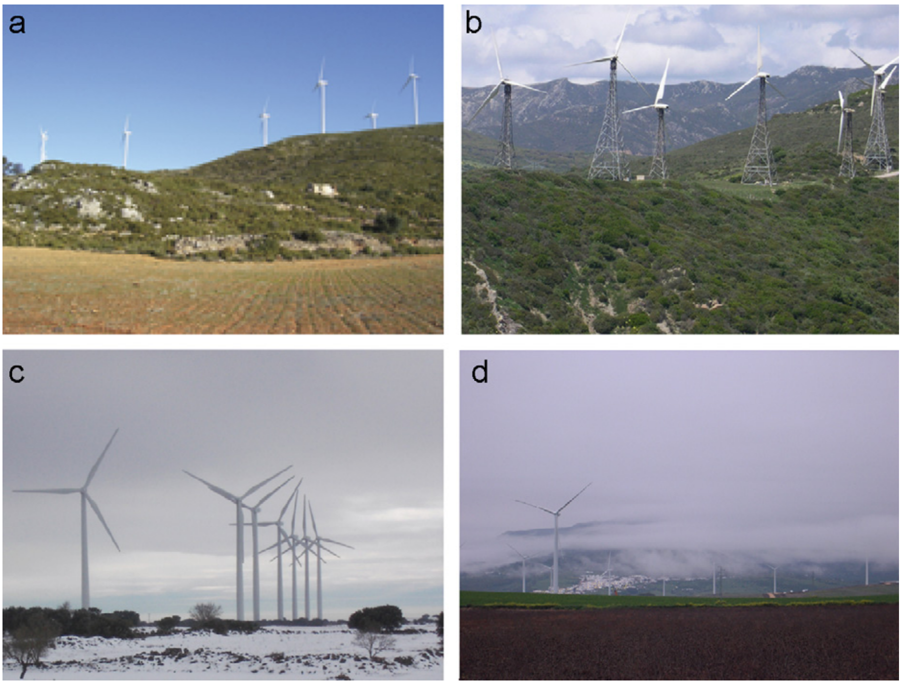

Fig. 5. The figure shows wind farms on a (a) clear day, (b) cloudy day, (c) snowy day and (d) foggy day.

evaluation is (Fig. 4)

$$I_{cl} = \begin{cases} 0 & \text{for } 0 < x \leqslant 5, \\ -\left(\dfrac{356}{10^9}\right)x^2 + \left(\dfrac{12}{10^4}\right)x - \left(\dfrac{56}{10^4}\right) & \text{for } 5 < x \leqslant 1563, \\ 1 & \text{for } 1563 < x \leqslant 1700, \end{cases} \tag{2}$$

where I_{cl} is the aesthetic impact due to colour and x the CIELAB points.

Table 1
Climatology values

Climatology i	Climatology value X_i
Clear day	1
Other	0.75
Precipitation	0.5
Fog	0.25

At zero CIELAB points, the turbine is camouflaged in the background sky and no impact is experienced. The higher the colour differences the greater the impact. Thus we see that it is important for the colour of the turbines to blend with the colour of the background surroundings. Turbines in the Nordic countries, for example, generally have an off-white or mid-grey tone to match the colour of the cloudy sky and the outer gel-coat of the blades is often painted with a matt finish to minimise reflections [32].

3.3. The climatology coefficient β^*

Visibility and colour will depend on the atmospheric conditions of the area between the object and the observer [27,31]. For example, fog can radically reduce the visible area of a turbine and the colour reflected from it (Fig. 5d)). Thus, the impact due to visibility and colour must be corrected by the atmospheric coefficient β^*:

$$I'_{\mathrm{v}} = \beta^* \cdot I_{\mathrm{v}} \quad \text{and} \quad I'_{\mathrm{cl}} = \beta^* \cdot I_{\mathrm{cl}}, \tag{3}$$

where I'_{v} and I'_{cl} are the aesthetic impacts due to the visibility and colour of the wind farm, respectively, corrected by the atmospheric coefficient, I_{v} is the visual impact due to the ratio of the area occupied by the turbines in view with respect to the area of the background view, I_{cl} is the visual impact due to the ratio of the colour of the turbines with respect to the background, and β^* is climatology coefficient.

The climatology coefficient is a measure of the average atmospheric conditions of a region. Calculation of the climatology coefficient required the use of another group of five experts. The experts were asked to assign values to different types of climatology, the results of which are shown in Table 1. The clearer the days, the more easily the farm can be seen and so the higher the impact, whereas foggy days hinder sight of the park and can reduce the visual impact considerably. The data on the climatology were obtained from the Spanish Institute of Meteorology. From the information analysed, four types of weather conditions were identified, namely days of fog, days of moderate precipitation (e.g. rain, snow), clear days, and others such as cloudy days. Consequently, β^* is calculated from

$$\beta^* = \sum_{i=1}^{n} P_i(\beta^* = X_i) \cdot X_i, \tag{4}$$

where X_i is the value assigned by experts to climatology and P_i is the probability that climatology i occurs in a given day of the year, i.e. the number of days of climatology i throughout the year divided by the number of days in the year.

Table 2
Climatology coefficients calculated for the cities of Valencia (Eastern Spain) and San Sebastián (Northern Spain)

City	X_i	Average number of days per year with X_i	$P(\beta = X_i)$	$P(\beta = X_i) \cdot X_i$
Valencia	1	91	0.25	0.25
	0.75	202	0.55	0.42
	0.5	62	0.17	0.08
	0.25	10	0.03	0.01
			$\beta^*_{\text{Valencia}}$	0.76
San Sebastián	1	37	0.10	0.10
	0.75	54	0.15	0.11
	0.5	177	0.48	0.24
	0.25	97	0.27	0.07
			$\beta^*_{\text{San Sebastian}}$	0.52

Data taken from the Spanish National Institute of Meteorology for the period 1971–2000.

Table 3
The climatology coefficient β^* of each wind farm

Wind farm	$P(\beta = 1)$	$P(\beta = 0.75)$	$P(\beta = 0.50)$	$P(\beta = 0.25)$	β^*
A (Cuenca, Spain)	0.00	0.70	0.28	0.03	0.67
B (Tarifa, Spain)	0.24	0.52	0.21	0.04	0.74
C (Valencia, Spain)	0.35	0.55	0.17	0.03	0.76
D and E (Cardiff, Wales)	0.17	0.09	0.49	0.25	0.55

Two examples of the calculation of the climatology coefficient for two cities of Eastern and Northern Spain are shown in Table 2. The Valencian climatology coefficient is larger as this city enjoys more days of sunshine than does the northern city of San Sebastián, which is characterised by significant precipitation levels. Table 3 shows β^* for the three wind farm locations, Cuenca, Tarifa and Valencia.

3.4. Fractality

Mandelbrot stated that 'there is a fractal face to the geometry of nature' [33] remarking on the strong connection between fractals and the natural world. Fractality is quantified by the fractal dimension, D, which may be defined as a measure of the extent to which a structure exceeds its base dimension to fill the next dimension. Because nature builds many of its patterns from fractals, the fractal dimension it has been argued, identifies the naturalness of a pattern or an element [34]. Man-made structures such as wind turbines against natural backgrounds will generate an impact I_{f} which can be represented by contrasts in fractal values.

Findings reporting on the preferred fractal dimension of a pattern have not been very consistent, with values ranging from $1.3D$ to $1.8D$ as most preferred. Discrepancies may be the result of differences in methodological procedures [35], for example different modes of pattern representation ranging from sketches and drawings to computer-generated

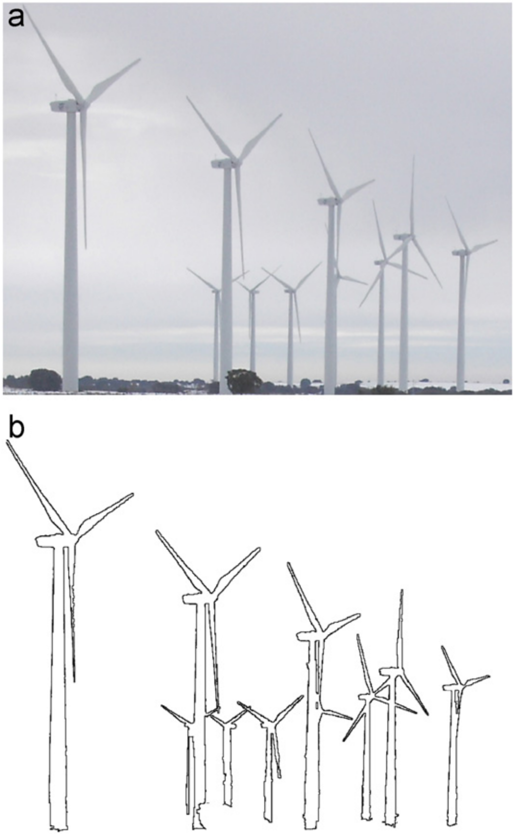

Fig. 6. Example of the extracted profile of various turbines for the analysis of fractality.

patterns [36,37], and differences in the population sample [38]. There are various methods of calculating the fractal dimension. This investigation will use the box counting method [35]. For this analysis the contour of the wind farm (Fig. 6) is extracted from the photograph. This can be done using Photoshop. The information is fed into the program 'fdc Linux', and D is calculated from

$$N(d) = 1/d^D, \tag{5}$$

where $N(d)$ is the number of boxes of linear size d necessary to cover a data set of points distributed in a two-dimensional plane.

The ratio 'fractal dimension of the farm versus fractal dimension of the main topographic line of the background (usually the skyline)' was calculated for five photographs and I_f was generated (Fig. 7):

$$I_\mathrm{f} = \begin{cases} 0 & \text{for } x = 0, \\ 1 & \text{for } 0 < x \leqslant 0.7 \text{ and } 1.7 \leqslant x \leqslant 2, \\ -0.3^{-1}x + 0.3^{-1} & \text{for } 0.7 \leqslant x \leqslant 1, \\ -2.04x^2 + 6.94x - 4.9 & \text{for } 1 \leqslant x \leqslant 1.7, \end{cases} \tag{6}$$

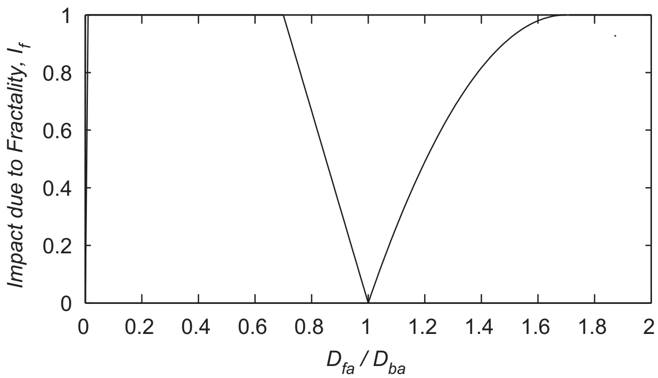

Fig. 7. Value function I_{f} as given by the experts.

where I_{f} is the aesthetic impact due to fractality, $x = D_{\mathrm{fa}}/D_{\mathrm{fb}}$, D_{fa} and D_{ba} are the fractal dimension of the farm and of the background, respectively.

For a view with no wind turbines ($D_{\mathrm{f}} = 0$), the impact due to fractality is zero. Assuming that a background is geometrically planar ($D_{\mathrm{b}} = 2$), impact will reach a maximum when a straight line is introduced into the scene. This value remains constant as more turbines, and thus more lines, are incorporated into the landscape up to the point where adding further turbines will start to convert a group of lines into a plane. At this point ($D_{\mathrm{f}} = D_{\mathrm{b}} = 0.7$), the impact starts decreasing and becomes zero when D_{f} reaches the value of 2 and the fractal ratio is unity. The remainder of the value function shows impact increasing as more planes are created on top of a planar background. As three-dimensionality is approached, the impact generated by the contrast against a planar background is again at its highest.

3.5. Continuity

Continuity refers to the silhouette enveloping a group of objects and is measured in terms of the number of "turns" in the silhouette. An envelope can turn depending on the layout of the turbines and on the line defining the topography of the area (Fig. 8), making the farm appear more or less continuous with respect to the background. Generally for a wind farm, the background definition line will be the horizon, however this may change depending on the position from which the farm is viewed. Therefore it is necessary to determine the topographic lines of definition carefully prior to calculations.

The difference between the number of turns of the wind farm envelope and the number of turns of the background envelope will affect impact perception [34,39]. The smaller the difference, the smaller the visual impact and optimal continuity is reached when this value is zero. We have found that the impact resulting from continuity difference can be calculated as follows:

$$I_{\mathrm{ct}} = f(1.05^{|t_{\mathrm{wf}} - t_{\mathrm{tl}}|}), \tag{7}$$

Fig. 8. The concept of continuity. In this picture the number of turns of the wind farm is 5 and the number of turns of the topographic line is 0.

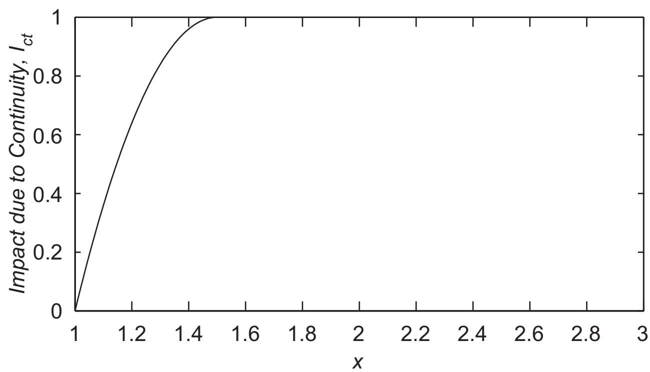

Fig. 9. Value function I_{ct} as given by the experts.

where I_{ct} is the aesthetic impact due to continuity and $|t_{wf} - t_{tl}|$ is the modulus of the difference between the number of turns of the wind farm and the number of turns of the topographic line.

Wind farms often consist of multiple layers of turbines. For example, in a flat expanse of land, wind turbines may be placed along parallel lines one behind the other. In this case, the impact induced by the continuity of each layer (lines) would decrease the further away the layer, and we find that this relationship can be represented by

$$I_{ct} = f\left(\sum_{j=1}^{N}\left(\frac{2^{N-j}}{2^N - 1}\right) \cdot (1.05^{|t_{wf}-t_{tl}|_j})\right) \tag{8}$$

where I_{ct} is the aesthetic impact due to continuity, N is the number of layers $N \in \mathbf{N}$, and j is the number describing the position of the layer.

Similarly to visibility, colour and fractality, a value function for continuity was obtained from expert assessment (Fig. 9):

$$I_{ct} = \begin{cases} -4x^2 + 12x - 8 & \text{for } 1 \leqslant x \leqslant 1.5, \\ 1 & \text{for } 1.5 \leqslant x \leqslant 3, \end{cases} \tag{9}$$

where $x = \sum_{j=1}^{N} (2^{N-j}/2^N - 1) \cdot (1.05^{|t_{wf} - t_{tl}|_j})$.

Fig. 9 shows the impact induced by the continuity effect increasing with the difference between the number of turns of the envelope of the wind farm and the number of turns of the topographic lines. When x approaches 1.5, the continuity impact reaches a maximum value of unity.

"Turbines should be sited in distinct units of uniform density" [40]. Möller [11] suggested that under certain conditions a decrease in the number of turbines by about 40% and an increase in installed capacity of 20% do not add to the comparative impact. Rather, impact is caused by the loss of homogeneity in the distribution of the turbines.

4. Operational definition of OAI_{WF}

The Indicator OAI_{WF} is derived from the mathematical combination of I_v, I_{cl}, I_f and I_{ct}. These variables are put together in a formula which takes the form of a weighted sum

$$OAI_{WF} = \beta^* \cdot (0.64 \cdot I_v + 0.19 \cdot I_{cl}) + 0.09 \cdot I_f + 0.08 \cdot I_{ct}. \tag{10}$$

The weights are given by a panel of seven experts in a Delphi procedure [41,42] and analysed using a multicriteria approach by means of an AHP analysis. The program Expert Choice 2000 was used to carry out the calculation of the weights. Greatest importance was attributed to visibility, which was considered more than three times as important as the second most important attribute, colour. Fractality and continuity were assigned smaller weights, but were still significant.

5. Application of OAI_{WF} to five wind farms

OAI_{WF} was applied to study the objective aesthetic impact at close-up view of five different wind farms located throughout Spain and Wales. Given the location of these areas, differences in weather conditions and vegetation patterns can be expected. The analysis of farm A (Region of Cuenca, Spain) took place during the winter on a dry-land area, whereas the green natural parks surrounding farm B (Region of Tarifa, Spain) were the result of summer rains and a summer sun which was also highly present in the rocky areas of farm C (Region of Valencia, Spain). Farms D and E (Cardiff, Wales) on the other hand were part of a green landscape, representative of the high precipitation in the area. The necessary data were collected for each of the wind farms according to the data collection protocol described in Section 2.4.2.

5.1. Analysis for the climatology coefficient β^*

First, the climatology coefficient β^* was calculated for each farm as described in Section 3.3. The atmospheric data used were obtained from the Spanish Institute of Meteorology and the Meteorological Office UK websites. The resulting values for β^* were 0.67, 0.74, 0.76 and 0.55 for Cuenca, Tarifa, Valencia and Cardiff, respectively (Table 3). The lower β^* for Cuenca as compared to the other two Spanish provinces results from to the fact that Cuenca is situated in inland Spain, and is subjected to colder weather conditions in winter and has less of the sunny Mediterranean climate of the other two regions. A similar situation occurs in Cardiff, a region exposed to high precipitation levels and occasional fog.

5.2. Analysis for I_{v}, I_{cl}, I_{f} and I_{ct}

Wind Farm A is situated on a flat expanse of land, on either side of the motorway connecting Valencia and Madrid. It was inaugurated in 2005 and consists of 33 tubular turbines generating 49.5 MW, with an annual electricity production of 120 GWh y^{-1}. Five different positions from which the wind farm can be viewed were identified: two views along the motorway, two others from two different rural roads either side of the motorway, and a final view from a restaurant by the city's exit to the motorway. Close-up-view photographs were taken from each position. Seven pictures were analysed for visibility, another seven for continuity and six for fractality. The analysis for colour was carried out on a different day, when the weather conditions provided clear views of the farm.

The impact of one of the main wind farms in Tarifa (Wind Farm A) was evaluated next. Tarifa is one of the pioneering zones for wind energy in Spain. This particular wind farm consists of 50 turbines rated at 150 kW situated in an environmentally protected natural park in a mountainous area, such that its accessibility is restricted to a main road, a rural road and one scenic view-point. The wind turbines differed in design, with most turbines exhibiting truss towers as opposed to tubular towers. A total of five photographs were analysed for visibility, five more for colour, four for fractality and another five for continuity.

Wind farm C consists of 25 turbines of 21 MW capacity and is located on a rocky and agricultural Valencian landscape. Four views of the farm were identified; three from three different fields nearby and one from a road leading into the town. Seven pictures were studied for visibility, four for colour, six for fractality and seven for continuity.

Finally, the two Welsh farms were analysed. Wind Farm D comprises 16 turbines of 21 MW capacity and is located at the top of a forested mountain in a region with few inhabitants. The only close-up view possible of this site is from a walkway high up the mountain. Wind Farm E has been built on a field in the vicinity of two villages, and consists of 20 turbines, with 9 MW capacity. Four pictures were analysed for visibility, fractality and continuity, and two others were used to study colour contrasts.

Fig. 10 shows examples of the pictures analysed for visibility for each of the wind farms, A, B, C, D and E.

The average values for visibility, colour, fractality and continuity were calculated for the farms and for the background views in the respective photographs. The corresponding ratios were computed and translated into values of I_{v}, I_{cl}, I_{f} and I_{ct} using the value functions introduced above. The results of these analyses are presented in Table 4.

5.3. The objective aesthetic impact

Inserting the values for I_v, I_{cl}, I_f and I_{ct} into OAI_{WF} as given by Eq. (10), the objective aesthetic impacts of the wind farms are, in order from most impacting to least impacting, 0.58 for Wind Farm B, 0.54 for Wind Farm A, 0.42 for Wind Farm C, 0.33 for Wind Farm D, and 0.28 for Wind Farm E (also shown in Table 4).

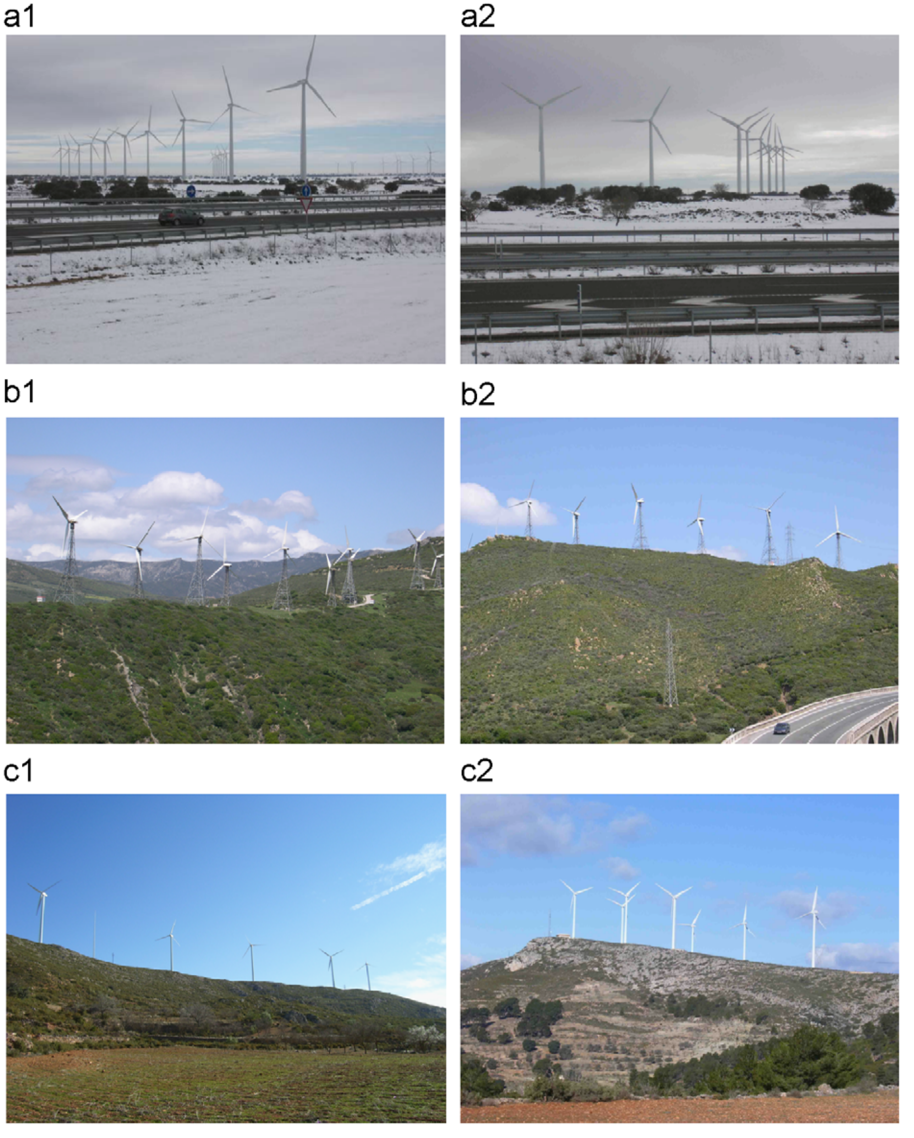

Fig. 10. Examples of photographs used in the analysis of visibility, of: (a) Wind Farm A either side of the motorway, (b) Wind Farm B from two different positions, (c) Wind Farm C from two different fields, (d) Wind Farm D taken from a walkway, (e) Wind Farm E from two different locations. Photographs (a1), (b1), (c1), (d) and (e1) were used for the social validation.

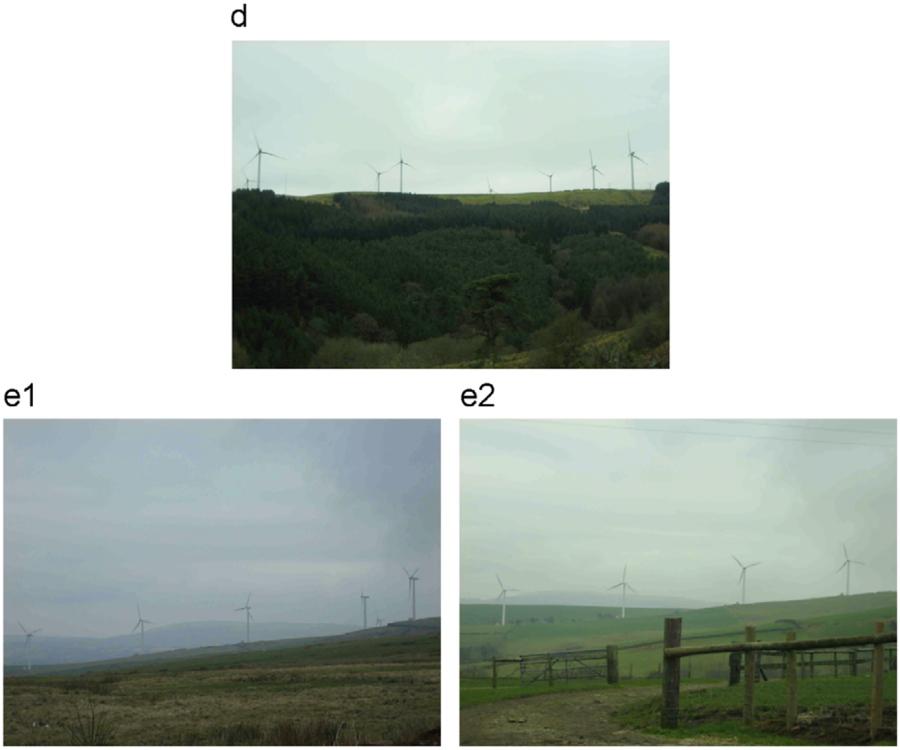

Fig. 10. (*Continued*)

Table 4
I_v, I_{cl}, I_f, I_{ct}, and OAI_{WF} calculated for the five wind farms

Wind farm	I_v	I_{cl}	I_f	I_{ct}	OAI_{WF}
A (Cuenca, Spain)	0.96	0.61	0.37	0.14	0.54
B (Tarifa, Spain)	0.91	0.59	0.47	0.37	0.58
C (Valencia, Spain)	0.53	0.84	0.30	0.22	0.42
D (Cardiff, Wales)	0.57	0.42	0.32	0.68	0.33
E (Cardiff, Wales)	0.51	0.44	0.43	0.20	0.28

5.4. Discussion of results

A combination of a high degree of visibility ($I_{v_B} = 0.91$), moderately high contrasts in colour between the turbines and the background ($I_{cl_B} = 0.59$), and a sunny climate with low precipitation levels ($\beta^*_{\text{Tarifa}} = 0.74$), makes Wind Farm B the most impacting of the five sites analysed. Although the farm is located in an environmentally protected, mountainous area and is thus of limited accessibility to observers, the elevated topography of the land and the farm's proximity to nearby, highly frequented roads, make the turbines very

noticeable. The farm consists of a large number of truss-tower turbines and so it is not surprising to see that the farm's I_f of 0.47 exceeds that of the other four farms. Further, because of the hilly nature of the landscape at location B, the turbines are placed in a discontinuous manner with respect to the main topographic line of the background. Thus, Farm B's continuity impact ($I_{ct_B} = 0.37$), is nearly three times that of the next most impacting wind farm A, which is located on flat land.

Wind Farm A, is situated inland, in a typically misty region, characterised by cold winters. The farm is highly frequented as it is sited next to a motorway leading to the Spanish capital city, Madrid. This farm's visibility is greatest, with its I_v value almost double that of the least visible farm E ($I_{v_A} = 0.96$; $I_{v_E} = 0.51$) and its colour contrasts are fairly high ($I_{cl_A} = 0.61$). However, the typically cloudy and misty weather conditions ($\beta^*_{\text{Cuenca}} = 0.67$) significantly reduce these values which, in combination with a lower fractality impact ($I_{f_A}) = 0.37$) and very low I_{ct} of 0.14, contribute to place the overall visual impact of Wind Farm A just below that of Wind Farm B.

A moderately low fractality too ($I_{f_C} = 0.30$), as well as a low visibility ($I_{v_C} = 0.53$) contribute to make Wind Farm C least impacting of the Spanish wind farms. On the other hand, the sunny weather conditions ($\beta^*_{\text{Valencia}} = 0.76$) guarantee a strong contrast between a blue sky and the white shades of the turbines and hence the largest I_{cl} out of the five farms with a value of 0.84. It should be noted that high values of I_{cl} are characteristic of older farms, whereas new turbines are painted such that their colour approximates that of the background sky.

Both Welsh farms exhibit very low visual impact values. Colour contrasts are relatively low ($I_{cl_D} = 0.42$; $I_{cl_E} = 0.44$) because the turbines have been painted white to match the colour of the sky, typical of a region prone to precipitation and fog ($\beta^*_{\text{Cardiff}} = 0.67$). Further, and similarly to Wind Farm C, both farms consist of fewer turbines than farms A and B and hence have a smaller visibility impact ($I_{v_D} = 0.57$; $I_{v_E} = 0.51$). The fractal value of Wind Farm D is relatively low, whereas that of E is rather high ($I_{f_D} = 0.32$; $I_{f_E} = 0.43$). This is because Farm E is situated in a grass field away from any trees or objects that could contribute to making a fractal skyline and thereby reduce the fractality ratio. Finally, the view of Wind Farm D suggests that the turbines have been placed in random order whereas Wind Farm E shows alignment with the background topography. Hence the continuity impact is higher at D ($I_{ct_D} = 0.68$; $I_{ct_E} = 0.20$).

6. Validation of OAI_{WF}

OAI_{WF} has been designed using a significant amount of expert input. However, it is the general public which is ultimately going to judge the aesthetic impact of the wind farm and so public opinion cannot be omitted from any analysis [43]. An indicator should be validated by three different groups of people, by the designers during the design process (Sui validatio), by scientific representatives who validate the output (Scientatis validatio), and by society itself, who are the impacted and the end-users of the indicator (Societatis validatio) [22,23]. Sections 3–5 have dealt with the first two validations. This section will look at the social validation.

The aim of the social validation is to ensure that the indicator results reflect public preferences. The indicator has ordered the wind farms according to their aesthetic impact (B > A > C > D > E), and this order should correspond to the order chosen by the public.

Table 5
Table showing the possible sequences (s_i) within a combination, the number of people choosing a particular sequence (N_i) and the probabilities related to each sequence

Combination	s_1	s_2	N_1	N_2	$P(s\|N,H_1)$	$P(s\|N,H_0)$	$\frac{P(s\|N,H_1)}{P(s\|N,H_0)}$	$P(H_1\|N,s)$
AB	A > B	**B > A**	31	72	4.89×10^{-29}	9.86×10^{-32}	495.81	0.9980
AC	**A > C**	C < A	63	40	1.57×10^{-31}	9.86×10^{-32}	1.59	0.6143
AD	**A > D**	D < A	17	3	4.18×10^{-5}	9.54×10^{-7}	43.80	0.9777
AE	**A > E**	E < A	16	4	9.83×10^{-6}	9.54×10^{-7}	10.31	0.9116
BC	**B > C**	C < B	97	6	6.72×10^{-12}	9.86×10^{-32}	6.82×10^{19}	1
BD	**B > D**	D < B	18	2	2.51×10^{-4}	9.54×10^{-7}	1.26×10^{-4}	0.9962
BE	**B > E**	E < B	17	3	4.18×10^{-5}	9.54×10^{-7}	43.80	0.9777
CD	**C > D**	D < C	15	5	3.07×10^{-6}	9.54×10^{-7}	3.22	0.7631
CE	**C > E**	E < C	18	2	2.51×10^{-4}	9.54×10^{-7}	1.26×10^{-4}	0.9962
DE	**D > E**	E < D	16	4	9.83×10^{-6}	9.54×10^{-7}	10.31	0.9116

Five photographs, each a representative close-up view of a wind farm (Fig. 10), were chosen and passed in a survey to a total of 123 people. The photographs of Wind Farms B and C were taken on clear days, whereas those of Wind Farms A, D and E were taken on typical days of precipitation. The subjects, who were students and teachers of the engineering and social-sciences disciplines, were asked to order the photographs according to how impacting they considered each wind farm to be. A total of 103 people compared Wind Farms A, B and C with each other. Thus, each person evaluated three paired combinations (A–B, A–C and B–C). Another 20 subjects performed pair-wise comparisons of the remaining seven combinations (A–D, A–E, B–D, B–E, C–D, C–E and D–E). For all the evaluations, the subjects were asked to record why they made the choice that they made. No further information or material, other than the photographs themselves, was given to them so as not to bias their judgement.

6.1. Consensus between indicator results and the order chosen by the subjects

The results of the survey are shown in Table 5. The left-hand side of the table shows the 10 possible pair-wise combinations, as well as the sequences that may be chosen within each combination. For example for the combination A–B, the possible sequences are A preferred over B (A > B) and B preferred over A (B > A). The number of people choosing each specific sequence is also given, and the preferred sequences are written in bold. Additionally, the sequences which match the order given by the indicator have been underlined. The table shows that for both indicator and sample population, the chosen sequence according to aesthetic impact is: B > A > C > D > E.

6.2. Subjects' decisions according to preferences

To verify the validity of the subjects' decisions, it was necessary to ensure that the subjects indeed chose each sequence according to some preference and not in a random manner. Thus we need to confirm that the probability the subjects decided on

a sequence according to some preference is statistically significant. This probability is given by Eq. (11):

$$P(H_1|N,s) = \frac{P(s|N,H_1)\cdot(1-p_0)}{P(s|N,H_1)\cdot(1-p_0)+P(s|N,H_0)\cdot p_0}, \tag{11}$$

where

$$P(s|N,H_1) = \frac{N_1!N_2!}{(N_1+N_2+1)}, \tag{12}$$

$$P(s|N,H_0) = (p_0^{N_1})\cdot(1-p_0)^{N_2}, \tag{13}$$

where $P(H_1|N,s)$ is the probability that the subjects decided according to some preference, $P(s|N,H_1)$ is the probability that sequence s was chosen according given preferences, $P(s|N,H_0)$ is the probability that sequence s was chosen at random, H_1 is the hypothesis that sequence s is chosen due to preferences, H_0 is the null hypothesis that sequence s was chosen at random, p_0 is the probability of the null hypothesis, s is the preferred sequence within a pair, e.g. sequence A over B, N is the number of subjects evaluating a combination, and N_i is the number of people choosing sequence i.

The sample size of five photographs was used to reduce the probability that the subjects choose a sequence at random. A sample size of five gives 10 possible combinations. Under the null hypothesis and assuming that the probability of choosing any one sequence is equal to 0.5, the probability that the subjects choose a sequence of photographs at random is reduced to 0.1%.

Table 5 shows that the subjects had a preference for a specific sequence in eight of the 10 sequences. In these cases the probabilities are greater than 90%, six of which surpass the 95% boundary. These values are statistically significant. Only two cases exist for which the subjects' answers are not as highly consistent. These are A > C with a probability of 61% and C > D with a probability of 76%. The former case exhibits the lowest probability. However, the chance that the subjects did not evaluate the wind farms at random is still 1.6 times higher than if they had. In this case it is necessary to study the reasons the subjects gave for selecting one sequence over another. Combination C–D also shows a lower probability than for most other cases, but nevertheless, the odds that subjects have chosen according to preferences as opposed to randomly are 3 to 1.

7. Discussion

7.1. Preferences and indicator variables

For each paired combination, the subjects were asked to select the most impacting wind farm, and record the characteristics which made one wind farm more impacting than another. One hundred and three people evaluated three combinations each, and another 20 subjects evaluated the remaining seven combinations. A total of 449 evaluations were made.

Within these evaluations, visibility and colour were the most mentioned characteristics, in 30% and 21% of the responses respectively (Table 6). Furthermore, the atmospheric conditions exhibited in the photographs were associated with colour in over 87% of the evaluations, but only 13% associated climate with visibility. Impacts due to visibility and

Table 6
Percentage of survey responses recording indicator variables and subjective variables

Variable	Survey responses (%)
Indicator variables	
Visibility	30
Colour	21
Climatology	20
of which associated with visibility	13
of which associated with colour	87
Fractality	8
Continuity	10
Subjective variables	
Natural vs. Built	13
Others	10

colour have greatest weight in OAI_{WF}, and both of them are equally corrected by the climatology coefficient which represents weather conditions. However, the subjects were inclined to associate atmospheric conditions more with colour than with visibility. This is because only photograph E displayed any type of precipitation (in this case, fog) between the observer position and the turbines, which could reduce the visibility of the farm. Hence, only for this wind farm was it possible to comment on the effect of weather conditions on visibility. Additionally, all photographs shown to the sample population were of close-up views. For close-up views, as opposed to middle-plane and far-plane views, higher levels of precipitations may be needed for visibility to be affected. However, further study is required on this issue.

The next most frequently mentioned characteristics can be related to what OAI_{WF} refers to as fractality, and continuity. These were mentioned by 8% and 10% of the evaluations respectively. The higher levels of fractality in Wind Farm B were perceived by the subjects who stated that against the "natural landscape", the grid-like structure of truss-towers turbines, as opposed to tubular-tower turbines, stood out for example like "military helicopters, making them far more impacting". The association with helicopters is also partly related to the dynamic properties of a wind turbine. For simplicity the variables considered in this study are ones which can be measured from still-life pictures, but moving turbine blades could affect aesthetic impact differently to static blades. Continuity was more debated. Most subjects agreed with the indicator in that a turbine layout which follows the topography of the background is less impacting, whereas 2% of the evaluations stated that it is precisely the "regiment-look" that a farm acquires when its turbines are too aligned with the surroundings, which make it the more impacting. However, this was the opinion of only a small number of subjects who undertook the survey, although it is nevertheless a point worthy of consideration in future studies.

Another concept mentioned by the sample population is naturalness versus artificiality. 13% of the evaluations commented that once a landscape has already undergone construction, further building will not have as great an impact as if it had occurred on virgin land. This is a principle which relates to cognition and hence the subjective part of the indicator; the association that human intervention "hurts" the environment is part of a subjective feeling. The indicator does however relate visual impact to artificiality by means

of the fractality value function which represents a confrontation between straight, man-made lines and natural fractals. However, because the background fractal dimension is measured from the skyline alone, an improvement might be possible through including all the other features contained in the background. This idea was considered initially, but was finally abandoned because the complexity involved. Further subjective aspects mentioned by the individuals include feelings of relaxation when viewing photographs B and D and preferences for certain farms because they remind the viewers of their home. Analysing the cognitive aspect of visual perception would require cognitive, dimensional analysis of people's preferences for wind farms. Such studies have mainly involved the general landscape [43,44], but psychological research specific to aesthetic impact of wind power has been very limited [45,46]. The authors are currently working on this investigation and hope to unite both objective and subjective aesthetic impact of wind farms.

7.2. Preferences and ordering

For both the indicator and the subjects, the selected order of impact was B > A > C > D > E. What is more, the variables which make up the indicator are also reflected in the survey evaluations. Wind Farm B was selected as most impacting by the subjects because they perceived it as highly visible and obtrusive against the natural background. This relates to the elevated $I_{\mathrm{v_B}}$, $I_{\mathrm{cl_B}}$, $I_{\mathrm{f_B}}$, and $\beta^*_{\mathrm{Tarifa}}$ values given by the indicator. Weather conditions influenced the sequence chosen; precipitation in A minimised colour contrasts and thus visual impact. The already urbanised landscape of photograph A also mitigated farm A's impact (Table 7).

Table 7
Table showing the possible sequences (s_i) within a combination, the percentage of people choosing a sequence (N_i (%)) for a given combination, and the main reasons/variables (Table 6) stated by the population sample for selecting that sequence

Combination	s_1	N_1 (%)	Decisions variables for choosing s_1	s_2	N_2 (%)	Decision variables for choosing s_2
AB	A > B	30	Visibility	B > A	70	Climatology asso. with colour; natural vs. built
AC	A > C	61	Visibility	C > A	39	Climatology asso. with colour; natural vs. built
AD	A > D	85	Visibility	D > A	15	Natural vs. built
AE	A > E	80	Visibility; climatology asso. with visibility	E > A	20	Natural vs. built
BC	B > C	94	Visibility; fractality; natural vs. built	B > C	6	Climatology asso. with colour
BD	B > D	90	Visibility	D > B	10	Other
BE	B > E	85	Visibility; fractality; climatology asso. with colour	E > B	15	Other
CD	C > D	75	Colour	D > C	25	Continuity
CE	C > E	90	Climatology asso. with colour	E > C	10	Natural vs. built
DE	D > E	80	Climatology asso. with visibility and colour	E > D	20	Other

Sequence A > C is more controversial. It cannot be confirmed that the subjects selected this combination according to preferences. Nevertheless, the probability that they did not choose at random is greater than 60%. For the most part, the subjects based their decisions on the visibility of the wind farms. They stated that Wind Farm A is more impacting than Wind Farm C because it has a higher number of turbines and is therefore more visible. However, this impact is reduced significantly by the foggy conditions of the area as well as by the already urbanised landscape of photograph A. A similarly controversial situation occurs for the sequence C > D. The subjects observed higher colour contrasts in photograph C but were also impacted by the disordered layout of farm D.

The preference stated by the subjects for sequence D over E is associated with the climate conditions presented in the photographs. The evaluations stated that the fog strongly reduces visibility- and colour-contrasts in photograph E, making Wind Farm E less impacting. Incidental weather conditions are not accounted for by $\mathrm{OAI_{WF}}$. The indicator uses average weather conditions for the analysis, hence the similar impact values for both farms ($\mathrm{OAI_{WF_D}} = 0.33$ and $\mathrm{OAI_{WF_E}} = 0.28$).

7.3. Methodology

This work concerns the development of an indicator to assess the magnitude of the objective aesthetic impact generated by the construction of a wind farm on a given landscape, $\mathrm{OAI_{WF}}$. The role played by the experts in the identification of landscape values and landscape assessment is important. In an attempt to develop $\mathrm{OAI_{WF}}$ as objectively as possible, the approach taken in this study is analogous to the expert-based approach, widely used in landscape evaluation. Nevertheless, even though professional judgements can help assess the landscape, it is ultimately the non-professional public who evaluates it

Table 8
Symbols

Symbols	
OAI	Indicator of objective aesthetic impact
I	Impact
S	Area ($\mathrm{cm^2}$)
D	Fractal dimension (D)
z	Impact weights
β^*	Climatology coefficient
Indices	
WF	Wind farms
v	Visibility
cl	Colour
f	Fractality
ct	Continuity
fa	Farm
ba	Background
A	Wind farm A
B	Wind farm B
C	Wind farm C
D	Wind farm D
E	Wind farm E

[47]. Hence the need for the social validation of the indicator. The aim of the validation was to ensure that the order of the visual impacts of the wind farms as given by the indicator corresponds to the order as perceived by the people. Although consistency was achieved with statistically significant probability values in most cases, further study on subjective judgement is recommended. Integrating expert knowledge with public evaluative reaction constitutes an important step towards the holistic approach of landscape assessment, which is gaining more strength in landscape evaluation practice [17].

8. Conclusion

In this work we have developed a composite indicator for the objective aesthetic impact of a wind farm located in a defined landscape. The indicator combines measures of visibility, colour, fractality and continuity which can be taken from photographs, and includes weighting functions determined by expert opinion. Comparison of the indicator results with a population survey shows that the calculated indicator correctly represents the order of preference resulting from perception of impact.

Analysis of the data suggests that visibility, colour, fractality and continuity are representative objective measures of aesthetic impact of wind farms, but the indicator might be improved by a different treatment of the fractality of background features (Table 8). Close-up visibility with respect to climatology and dynamic properties of turbines also require further research. Finally, there is also a need to incorporate aspects of the subjective aesthetic impact in order to develop a general indicator of aesthetic impact of wind farms.

Acknowledgements

The authors would like to thank Professor Andrew Zisserman for his ideas on computer vision and guidance throughout the project. They would also like to express their gratitude to Professor Steven Roberts for sharing his expertise in statistical analysis and to Dr. Rafael Monterde for his contribution to the development of the indicator.

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